Performance of the EBIT calorimeter spectrometer[a)]

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The EBIT calorimeter spectrometer (ECS) is a new high-resolution, broadband x-ray spectrometer that has recently been installed at the Electron Beam Ion Trap Facility (EBIT) at the Lawrence Livermore National Laboratory. The ECS is an entirely new production class spectrometer that replaces the XRS/EBIT spectrometer that has been operating at EBIT since 2000. The ECS utilizes a 32-pixel x-ray calorimeter array from the XRS instrument on the Suzaku x-ray observatory. Eighteen of the pixels are optimized for the 0.1–10 keV band and yield 4.5 eV full width at half maximum energy resolution and 95% quantum efficiency at 6 keV. In addition, the ECS includes 14 detector pixels that are optimized for the high-energy band with a bandpass from 0.5 to over 100 keV with 34 eV resolution and 32% quantum efficiency at 60 keV. The ECS detector array is operated at 50 mK using a five stage cryogenic system that is entirely automated. The instrument takes data continuously for over 65 h with a 2.5 h recycle time. The ECS is a nondispersive, broadband, highly efficient spectrometer that is one of the prime instruments at the EBIT facility. The instrument is used for studies of absolute cross sections, charge exchange recombination, and x-ray emission from nonequilibrium plasmas, among other measurements in our laboratory astrophysics program. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2957925]

INTRODUCTION

Imaging x-ray spectroscopy is an active field of research for astrophysical instrumentation. Current generations of x-ray observatories use x-ray charge coupled devices for imaging with moderate spectroscopy and minimal timing. High-resolution spectroscopy is performed with dispersed instruments such as the reflection grating spectrometer on the XMM/Newton observatory and the transmission grating instruments on the Chandra observatory. All x-ray observatories that are currently in the planning stage include detector systems that combine imaging and high-resolution spectroscopy in the same instrument. A combined spatial-spectral instrument generates the most information about the emitter in the shortest exposure given the typically photon-starved conditions for cosmological sources. Nearly all, future, high-resolution spatial-spectral instruments for x-ray astrophysics are based on pixilated x-ray calorimeter run at very low temperatures, typically 0.05 K.

X-ray calorimeters have been in development for spaceflight since 1984 (Ref. 1) and have been used successfully for suborbital instruments,[2] and with limited success on orbiting observatories.[3] We have been very successful in leveraging the spaceflight development programs to perform laboratory astrophysics measurements on the ground. Over the past 15 years, our laboratory astrophysics program has studied x-ray emitting plasmas in the laboratory to validate and benchmark the atomic codes that are used to model astrophysical observations. This work has been vital to interpreting the spectroscopic observations from the current high-resolution x-ray spectrometers and will become even more important in the future with the next generation of high-resolution spatial-spectral instruments.

In our laboratory astrophysics program, we developed and deployed a laboratory version of the x-ray spectometer (XRS) instrument based on a 32-pixel x-ray calorimeter array running at 0.06 K and installed it at the Electron Beam Ion Trap (EBIT) facility at Lawrence Livermore National Laboratory (LLNL) in July, 2000. Since then the XRS/EBIT instrument has been running almost continuously, enabling an extraordinary number of unique measurements from direct excitation cross sections to measurements of charge exchange recombination in astrophysical plasmas (see Ref. 4 and references therein). We have now replaced the XRS/EBIT instrument with a new x-ray calorimeter instrument at the EBIT facility at LLNL. The new calorimeter instrument, the EBIT calorimeter spectrometer (ECS), was designed from the ground up to be a very low maintenance, largely autonomous spectrometer and to be a permanent installation at the EBIT facility. The ECS was completed and installed at the EBIT facility at LLNL in November, 2007. Here we briefly describe the ECS instrument and its performance, as installed at LLNL. Some of the initial science results are described in Refs. 5 and 6.

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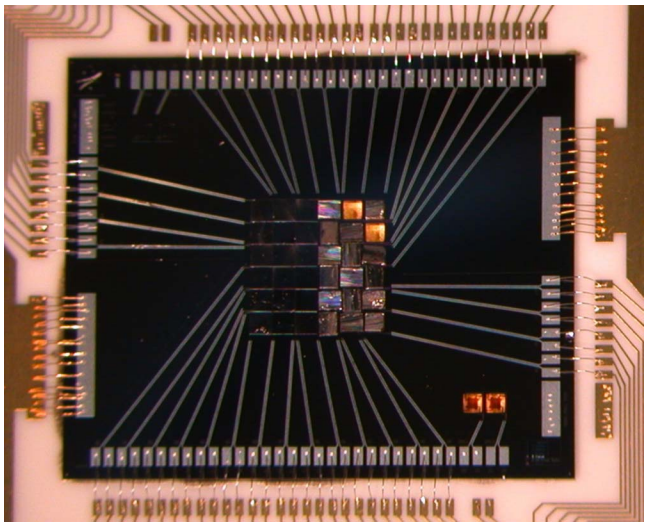

FIG. 1. (Color online) The 36 pixel ECS microcalorimeter array. The left side of the array includes the $624\times624\times8$ μm midband detectors and the right side of the array includes the $624\times500\times100$ μm high-energy detectors.

THE ECS INSTRUMENT

The ECS instrument uses a 32-pixel x-ray calorimeter array developed at NASA/GSFC for the Suzaku/XRS program. Each pixel is a thermal x-ray detector (see, for example, Ref. 7 and references therein) where an incident x ray is absorbed in an x-ray absorber material and the heat deposited by the absorption is sensed by an integrated thermometer. The x-ray absorber material is chosen for its opacity over the bandpass, fast thermalization, and low heat capacity. With the right choice of materials and careful design, extraordinary performance can be achieved with resolving powers over 3000 and a very large bandpass from a few eV to several MeV. In the ECS, the absorber material is HgTe that has been successfully used in both our x-ray quantum calorimeter sounding rocket program and in our XRS program. The ECS detector array, shown in Fig. 1, is divided into two subarrays: a midband array covering from 0.1 to 10 keV and a high-energy array covering from 0.5 to over 100 keV. Both subarrays are operated simultaneously at 0.05 K giving a total instrument bandpass of 0.1 to over 100 keV. The midband array consists of 625×625 μm^2 pixels with 8 μm thick HgTe absorbers giving a quantum efficiency of 95% at 6 keV. The high-energy array is similar with 625×500 μm^2 pixels but with 100 μm thick HgTe absorbers giving a much higher quantum efficiency at high energies, 32% at 60 keV.

The ECS detector array is housed in a laboratory version of the XRS detector assembly[8] with some important improvements to increase the gain stability and energy resolution. Specifically, we have improved the readout circuit by increasing the size of the load resistors from 90 to 120 MΩ (Ref. 8) to allow greater bias stability at 50 mK and have introduced infrared absorbing materials into the detector housing to decrease the sensitivity to infrared radiation. The refrigeration system is also substantially improved and much easier to operate than that on the predecessor XRS/EBIT spectrometer.

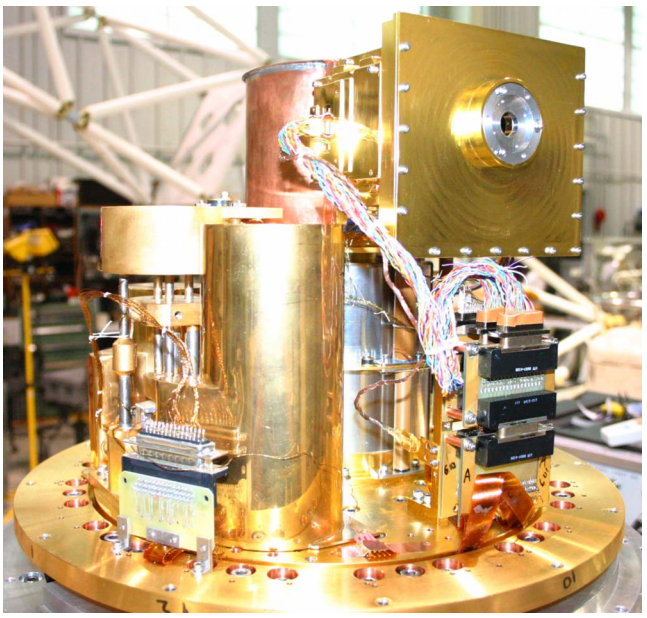

FIG. 2. (Color online) The ECS cryogenics package includes the detector assembly (upper right), the closed cycle He^3/He^4 refrigerator (front left), and the adiabatic demagnetization refrigerator (middle back). The package cools the calorimeter detector array to 0.05 K for over 65 h and requires only a 4.2 K interface, has no moving parts, and has no external plumbing.

The ECS cryogenics package, shown in Fig. 2, consists of a three stage cooling system that operates from a 4.2 K interface, requiring no external plumbing and no moving parts. A liquid nitrogen shielded liquid helium dewar, running at atmospheric pressure, provides the 4.2 K interface in the ECS. A similar system running in our laboratory operates from a commercial pulse-tube mechanical cooler and uses no cryogens. The ECS cryogenics package contains a Chase Cryogenics[9] closed cycle He^3/He^4 refrigerator to cool the detector assembly housing and to precool a magnetic refrigerator to 350 mK. An adiabatic demagnetization refrigerator[8] (ADR) then cools the detector array to its 50 mK operating temperature. The ECS refrigerator is a single shot system that operates at 50 mK for 65 h before needing a 2.5 h recharge cycle. During the recharge, both the He^3/He^4 refrigerator and the ADR are automatically cycled under computer control. The only user servicing is to fill the ECS's 25 l liquid nitrogen tank every 5 days, and the liquid helium tank every 21 days. Otherwise the operation of the spectrometer is entirely transparent to the user. The cryogen-free version of the ECS, which is in its final stages of assembly, is predicted to operate for over 200 h at 50 mK between 2.5 h recharge cycles and will require no servicing.

ECS PERFORMANCE

The ECS performance was benchmarked using both standard x-ray calibration sources and the EBIT instrument itself. Figure 3 shows a composite spectrum from the 18 midband channels of a ^{55}Fe electron-capture radioactive source. A fit to the natural line shape[10] yields a Gaussian instrumental function with a full width at half maximum (FWHM) of 4.5 eV at 6 keV. This performance was also realized after installation on the EBIT. Figure 4 shows a

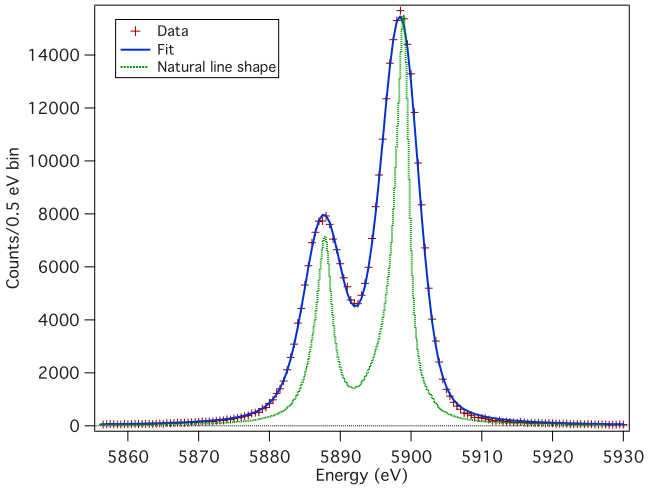

FIG. 3. (Color online) Spectrum of a ^{55}Fe electron-capture source producing Mn $K\alpha$ x-rays using the ECS spectrometer. A fit to the natural line shape (Ref. 10) yields a Gaussian instrumental function with a 4.5 eV FWHM at 5.9 keV.

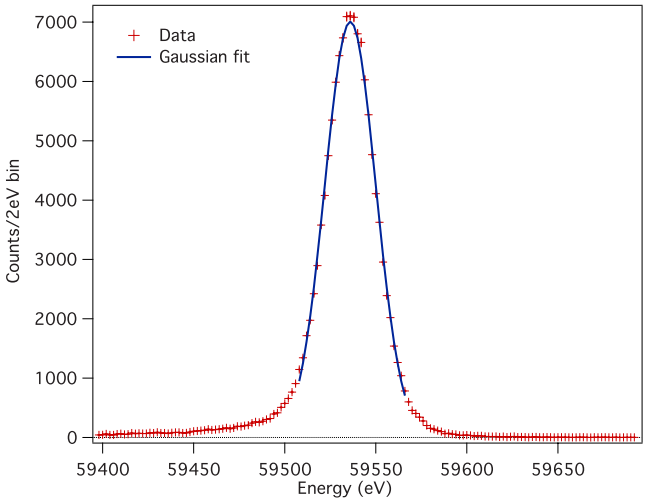

FIG. 5. (Color online) ECS spectrum of the 60 keV gamma line from the decay of ^{241}Am. The composite spectrum of all 14 high-energy pixels gives a Gaussian instrumental function and a small low energy tail with a 34 eV FWHM at 60 keV.

composite spectrum of x-ray emission from heliumlike Fe XXV and hydrogenlike Fe XXVI produced in the EBIT that also gives a Gaussian instrumental function with 4.5 eV FWHM. Similarly, the high-band pixels were characterized using gamma and x-ray emission from the decay of ^{241}Am. The fit to the 60 keV gamma line (shown in Fig. 5) gives a Gaussian instrumental function of 34 eV for the composite of the 14 high-energy pixels. Finally, the infrared blocking filters installed in the ECS aperture have ten times more transmission at 0.25 keV (T=30%) than the XRS/EBIT instrument and three times the transmission at 0.5 keV (T=60%), making the ECS an ideal instrument for observing L-shell emission from the light abundant elements.

The ECS uses the same real-time analysis package we constructed for spaceflight for the XRS program and have adapted for laboratory use for the XRS/EBIT. This provides real time, optimal,[11] event characterization and display, allowing the experimenter to perform real-time spectroscopy. Relative event time tagging is accurate to 10 μs and absolute time tagging is accurate to 80 μs.

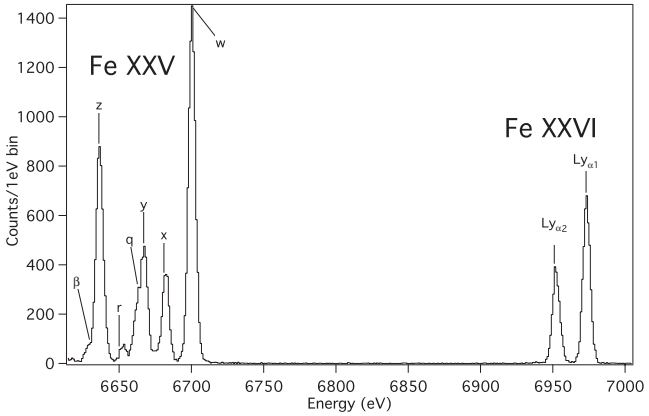

FIG. 4. ECS spectrum of highly charged Fe produced in the EBIT facility at LLNL. This is a composite spectrum of all 18 midband channels again yielding a Gaussian instrumental function with 4.5 eV FWHM at 7 keV.

The ECS spectrometer will be a workhorse instrument at the LLNL EBIT facility for the foreseeable future and, coupled with the extensive set of dispersive instruments at the facility, will provide detailed measurements of line emission from astrophysical plasmas in the laboratory. Planned experiments include L-shell charge exchange from the abundant elements Ne–Ni, absolute cross sections of direct excitation emission for L-shell emission from Ni and also the light elements Ne–Ca, and absolute cross sections of K shell emission. We are also currently developing the successor instrument to the ECS based on x-ray calorimeter detectors produced for the Constellation-X spaceflight program. The new spectrometer, to be delivered in 2010 and termed the transition edge microcalorimeter spectrometer, will be a hybrid system with 128 low-band detectors with 0.8 eV resolution from 0.1 to 1.5 keV, 128 midband detectors with 2 eV resolution from 0.1 to 10 keV, and 64 high-band detectors with 30 eV resolution and 60% quantum efficiency at 60 keV and a bandpass from 0.5 to 200 keV. The x-ray calorimeter has proven to be a productive and versatile detector on the ground and in spaceflight experiments and will continue to be one of the premier techniques for nondispersive x-ray spectroscopy for the foreseeable future.

ACKNOWLEDGMENTS

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